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Development, characterization, and processing of thin and thick inkjet-printed dielectric films

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ABSTRACT

This work introduces the material and electrical characterization of two dielectric inks for use with inkjet printing fabrication and the realization of fully-printed multilayer electronic structures. The dielectric inks are categorized by the thickness of their per-layer profiles, where SU-8 polymer and poly(4-vinylphenol)-based solutions are utilized to realize thick (>4 μm) and thin (< 400 nm) inkjet-printed dielectric films, respectively. The material formulations for each ink are outlined in detail in order to achieve the desired viscosity and surface tension for optimal printing with a Dimatix inkjet printing system. Once printability and processing techniques are tuned and established, various material and electrical characterizations are performed, including printed profile measurement, multilayer profile tendencies, thermal reflow processing, UV-ozone surface energy modification, relative permittivity extraction, leakage current density, and dielectric breakdown voltage. Finally, the demonstration of fully-printed post-processed on-chip capacitors utilizing both thin and thick dielectric inks in conjunction with a silver nanoparticle-based metallic ink is presented and compared with other inkjet-printed capacitors.

1. Introduction

Throughout the past decade, inkjet printing has gained extensive popularity as a fabrication method for electronic devices throughout a multitude of research and industrial fields. Using a drop-on-demand material system deposition, inkjet printing allows for a fully additive processing technique of electronic materials. This additive process contrasts typical methods of electronic fabrication, eliminating the need for cleanroom environments, hazardous chemical waste, and expensive photolithography masks and techniques [1].

Recent progress in the development of inkjet-printable ink formulations has led beyond purely conductive inks to the realization of printable dielectric films. Dielectric films are essential to the fabrication of any printed electronic device and are generally divided into two classifications based on their deposited thicknesses: thin (<1 μm) and thick (>1 μm). Thin dielectric films are essential for printed low-profile components such as metal-insulator-metal (MIM) capacitors and organic transistor gates [2–4], while thick dielectric films are used to process selectively-patterned dielectric substrates [5–7]. Combining conductive nano-particle based inks with dielectric inks, inkjet printing can be used to fabricate complex bottom-up electronic structures in a purely additive process [8].

The deposition of thick dielectric films is integral to a wide variety of electronic applications. The inkjet-printing of thick dielectric structures allows for the realization of multilayer device fabrication through selective patterning and deposition. Dielectric spacers find use in such multilayer structures as antennas, substrate integrated waveguides (SIWs), and via interconnects [9]. With large-scale thick film deposition, electrically diverse dielectric substrates can be printed on virtually any host substrate.

Commonly used as a photoresist in integrated circuit (IC) fabrication, SU-8 is a long-chain polymer that is deposited through spin-coating onto silicon wafers for high-aspect-ratio electronic

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device patterning [10–12]. Recent advances in inkjet printing have allowed for this polymer to go beyond its typical cleanroom use as a sacrificial mask towards a thick film dielectric for microwave devices. SU-8 polymer chains have two advantages for inkjet printing fabrication: low-temperature UV cross-linking (compared for instance to dielectric ceramics [13]) and high polymer content by weight while still maintaining a relatively low viscosity. Low-temperature processing is useful when dealing with organic substrates typically used with inkjet printing that may deteriorate at higher temperatures, such as paper and liquid crystal polymer (LCP). High polymer content allows for a thicker, more uniform layer-by-layer deposition, while low viscosity is required to be compatible with industrial inkjet printer cartridges.

The deposition of thin dielectric films is a fundamental feature for fabrication processes as it is needed in several situations, especially in multi-layer technologies. Thus, inkjet printing of thin dielectric films is a big achievement as it allows for the prototyping of dielectric coatings, capacitive coupling, and any device in which thin insulators are needed (i.e. MIM capacitors [14]). Moreover, it is worth noting that inkjet printing is a robust fabrication method that allows the combined deposition of thin and thick dielectric films based on the application. For instance high Q inductors with electrical bridges are realized by printing thick SU-8 films, and high Q capacitors are fabricated with thin insulators. These two discrete components can be combined to realize the high Q filters and resonators used in many electronic systems.

Thin dielectric layers are realized through the utilization of two polymer inks based on poly(4-vinylphenol) (PVPh) in different ratios in order to vary the permittivity (ε_r) of the printed film [15,16]. The solvent used to mix the solution is the Hexanol-6 while PVPh, which is a long-chain polymer, is cross-linked by Poly(melamine-co-formaldehyde) (PMF). It is important to underline that both PVPh and PMF have dielectric properties that contribute to the features of the final inks.

In order to pronounce the functionality of thick and thin inkjet-printable dielectric films, complete material characterization is performed in this work for two polymer-based inks. Chemical formulation is outlined in detail along with post-deposition processing techniques. Printed profiles are presented to outline surface uniformity characteristics. Surface treatment methods are investigated in order to optimize ink-to-substrate wettability for printed multilayer structures. Electrical properties such as leakage current and dielectric breakdown voltage are extracted from printed film samples for functional electrical characterization. Finally, inkjet-printed MIM capacitors utilizing both dielectric inks are demonstrated on a lossy silicon substrate as an application of the multi-layer, vertically-integrated printing process for on-chip and package-integrated post-processing.

2. Materials

2.1. Thick dielectric ink formulation

The SU-8 thick film dielectric ink is formulated using photoresists from the SU-8 2000 polymer series provided by MicroChem (MicroChem, Newton, MA, USA). The SU-8 polymer is typically used as a photo-resist in cleanroom photolithographic processes with its inclusion of Triaryl salt (SbF_6) for near-UV cross-linking. A cyclopentanone solvent (C_5 H_8 O) is also included in order to improve coating and adhesion properties upon deposition while also helping to increase the viscosity of the SU-8 polymer to that of the printable range.

In order to ensure printability with the Dimatix DMP-2800 inkjet printing platform, an ink viscosity within the range of 8–16 cP is desired. A second consideration for thick dielectric printing is the solid content of the material, where a higher solid content yields a thicker per-layer deposition. This higher solid content also results in a higher fluid viscosity, creating a printability contrast between the solid content and fluid viscosity of the resist materials. In order to achieve a high polymer solid content along with a low viscosity, a study of the viscosity of the SU-8 polymer with different weight percentages within a cyclopentanone solvent is performed. Table 1 outlines the measurements of the parametric analysis using a Gilmont falling-ball viscometer (Gilmont GV-2200).

The loading of different polymer contents of the SU-8 resist within the cyclopentanone solvent effectively tunes the viscosity and solid content of the resulting ink. The parametric analysis presented in Table 1 yields an optimal SU-8 polymer weight percentage of 35% with an ink viscosity of 13 cP. Further measurements of the prepared thick film dielectric ink yield a surface tension of 30 mN/m. These material properties are within the required ranges of printability for the Dimatix system, which allows for printed profile examination.

2.2. Thin dielectric ink formulation

In order to investigate the versatility of printing thin dielectric films, two PVPh-based dielectric inks are formulated. For simplicity they are referred to as ink1 and ink2. The recipe is composed of the following: poly(4-vinylphenol) (PVPh), a long-chain polymer (Product No. 436216, Sigma Aldrich), poly(melamine-co-formaldehyde) (PMF), a heat activated cross-linker (Product No. 418560, Sigma Aldrich), and finally the solvent 1-Hexanol.

Ink1 and ink2 have a different ratio by weight of PVPh and PMF, while the ratio between the solvent and the polymers is kept constant to 17:1 w/w%. In particular, ink1 is characterized by 1:10 w/w% ratio while ink2 is formulated with 1:1 w/w% ratio, between PVPh and PMF. Both PVPh and PMF are polymers with dielectric properties, so changing their ratio allows for the tuning of the permittivity (ε) and the loss tangent ($\tan\delta$) of the printed thin-film layer. In Table 2 the recipes (ratio by weight) of ink1 and ink2 are reported.

As previously stated, several tests are needed in order to verify the inks' printability with the desired Dimatix DMP-2800 printing platform. First, viscosity and the surface tension are measured for both PVPh inks. Viscosity is measured as 8.93 cP and 13 cP for ink1 and ink2, respectively. Surface tension is measured as 39 mN/m and 29.3 mN/m for ink1 and ink2, respectively. The requirements for the DMP-2800 are thus satisfied for both the viscosity and the surface energy and the inks are ready for profile tests.

3. Experimental

3.1. Thick dielectric ink processing

With the printability of the SU-8 ink established, 25 mm^2 square sample films of the SU-8 dielectric ink are printed directly onto a glass slide. Printing is performed with the platten at room

Table 1
Viscosity versus SU-8 polymer content within cyclopentanone solvent for SU-8 ink formulation.

Polymer w/w% in C_5 H_8 O	Viscosity (cP)
0	2
29	7.5
31	8
33	9
35	13